Friction velocity u_* and roughness length z_0 of atmospheric surface boundary layer in sparse-tree land[1]

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Abstract Sparse-tree land is one of the typical lands and can be considered as one typical rough surface in boundary layer meteorology. Many lands can be classified into the kind surface in the view of scale and distribution feature of the roughness elements such as agroforest, scatter planted or growing trees, savanna and so on. The structure of surface boundary layer in sparse-tree land is analyzed and the parameters, friction velocity u_* and roughness length z_0 are deduced based on energy balance law and other physical hypothesis. The models agree well with data of wind tunnel experiments and field measurements.

Key words: Sparse-tree land, Friction velocity, Roughness length

Introduction

Protection forest is one of the most frequently used measures to protect crops from strange wind and to reduce soil evaporation and soil erosion. Protection forest in farmland can be classified in three kinds (Cao 1983): One kind is shelterbelts. Second is sparse tree in farmland, generally called agroforest in China. This kind includes regularly and randomly planted or naturally growing trees in farming area. The third is cluster of trees. These three kinds of forest exist together in farmland area. The shelterbelts are general and the protective effect and aerodynamics were very deeply studied (Bradly 1983; Cao 1983; Eimern 1963; Jensen 1961; Plate 1971; Schwartz 1995; Wei 1987; Wang 1996; Zhang 1984; Zhu 1993). But the researches of aerodynamics of second and third were few. Only some micrometeorological measurements were reported (Li 1994; Lu 1983). Some related studies aimed at the surfaces with solid rough elements (Mashall 1971; Raupach 1980; Wooding 1973) and the physical characteristics of these elements are different from trees. It is important to know the relationship between the aerodynamics of the surface and the structure of sparse-trees because this is not only necessary to understand protection effect of the forest, but also helpful to provide parameters to climatic models. This paper will deduce the models of friction velocity and roughness length of surface boundary layer in sparse-tree land and demonstrate the models with data of wind tunnel experiments and field measurements.

Structure of surface boundary layer in sparse-tree land

In neutral stratification, surface wind velocity profile in open land is

$$u_0(z) = \frac{u_{*0}}{\kappa} \ln \frac{z}{z_{00}} \tag{1}$$

Where u_{*0}, $\kappa=0.4$, z_{00} are friction velocity, Karman constant and roughness length of the open surface respectively.

When the surface flow approached the sparse-tree land, the surface boundary layer change its structure and become relative stable, as the distance is far enough. The boundary layer can be roughly divided in three layers as follow (Fig.1):

First layer is the boundary layer immediately on the ground that is generated by the friction between airflow and the ground. This layer is very thin and its ceiling is under the tree height. The airflow of the layer is not uniform in horizontal because of the disturbance of the trees. But except for the area very close to trees, the wind velocity profile in the layer can be approximately expressed in logarithm

$$u'(z) = \frac{u'_*}{\kappa} \ln \frac{z}{z'_0} \tag{2}$$

Where u_*' and z_0' are friction velocity and roughness length of the surface respectively. And generally $u_*' < u_{*0}$. We call this layer "under layer".

Second layer is on "under layer", ranging from ceiling of "under layer" to the height about 2H. This

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layer is generated mainly by the friction between the air flow and the trees. The thickness of the layer is depended on stratification. The parameters such as friction velocity and roughness length are also influenced by the structure of the trees (canopy density and individual tree's porosity or permeability). We call this layer "roughness sublayer". The wind profile in the layer is

$$u(z) = \frac{u_*}{\kappa}\left(\ln\frac{z-d}{z_0} + \phi\right) \tag{3}$$

Where u_* and z_0 are friction velocity and roughness length of the layer respectively. ϕ is influence term to indicate the difference between logarithm profile and actual profile. d is zero-plane displacement, which is function of canopy density C of the trees (Guan, 1997)

$$d = \begin{cases} 0 & C \leqslant 0.116 \\ \frac{H}{a}\ln\frac{C}{C_0} & C > 0.116 \end{cases} \tag{4}$$

where a=2.735 is an empirical constant. C_0=0.116 is the maximum C for d=0

The third layer is on the "roughness sublayer", The wind profile in the layer is

$$u(z) = \frac{u_*}{\kappa}\ln\frac{z-d}{z_0} \tag{5}$$

Where all the symbols are same as equation (4). This layer is called "inertial sublayer"

We call "roughness sub layer" and "inertial sublayer" together as "internal boundary layer" (IBL).

Friction velocity u_* in IBL

According to the principle of constant flux in surface boundary layer, the momentum flux M down to the surface in IBL is equal to the sum of drag of the trees τ_1 and the stress of the ground τ_2 which are analyzed follow.

Drag of the individual tree is

$$\tau_1 = \frac{1}{2}C_T\rho HD(ru_{*0})^2 \tag{6}$$

where ρ is air density; H and D are height and crown width of tree respectively; r is relative approaching wind velocity to the tree; u_{e0} is geometrical mean wind velocity in open land integrated from z_0 to H. It was approximately expressed as (Zhu 1993)

$$u_{e0} = \frac{u_*}{\kappa}\ln\frac{H}{ez_{00}} \tag{7}$$

and C_T is drag coefficient of isolated tree which is expressed as (Guan, 1999)

$$C_T = \frac{1}{2}A(1-\alpha^2) \tag{8}$$

Where A=0.92 is empirical constant and α is permeability of isolated tree.

If the trees are considered as cylinder shape and tree density is one on ground area s, then

$$s = \pi (D/2)^2/C \tag{9}$$

considering (6) to (9), drag of trees on unit ground area is

$$\tau_1 = \tau_1'/s = \rho CAH(1-\alpha^2)(ru_{e0})^2/(\pi D) \tag{10}$$

The stress on ground is approximately expressed as

$$\tau_2 = \rho (ru_{*0})^2 \tag{11}$$

Based on the wind tunnel experiment and field measurement data the empirical relation of r and C was

$$r = 0.88e^{-4.0C} + 0.12 \tag{12}$$

with correlation 0.986.

Considering

$$M = \tau_1 + \tau_2 \tag{13}$$

$$M = \rho u_*^2 \tag{14}$$

and (6) to (11), then

$$\frac{u_*}{u_{*0}} = (0.88e^{-KC} + 0.12)\left[CAH(1-\alpha^2)\frac{1}{\pi\kappa^2}(\ln\frac{H}{ez_{00}})^2 + 1\right]^{1/2} \tag{15}$$

Model values and measurement in wind tunnel experiments and field of u_*/u_{*0} (Guan, 1997) are compared in Table 1. The model agrees well with the measurements.

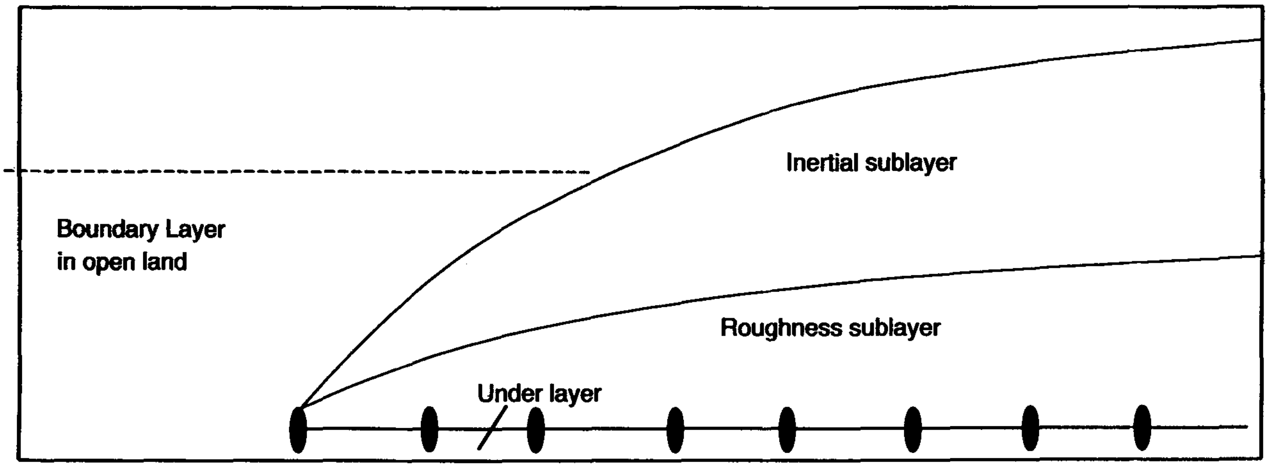

Fig. 1. Sketch map of structure of boundary layer in sparse-tree land (vertical distance not drawn to scale)

Table 1. Ratio of friction velocity u_*/u_{*0} in boundary layer above sparse trees to open land

	Wind tunnel experiment					Land measurement	
Canopy density	0.056	0.113	0.225	0.450	0.900	0.60	0.80
Measurement values	2.92	2.96	3.10	2.33	2.03	2.06	1.98
Model values	2.81	3.15	2.94	2.09	1.82	1.88	1.80
Errors	0.11	-0.09	0.16	0.24	0.21	0.18	0.18

Roughness length of IBL

From (3) we deduce

$$\frac{z_0}{H} = (1-\frac{d}{H})\exp(\phi - \kappa\frac{U_H}{u_*}) \quad (16)$$

If the approaching wind velocity relative to open land at height H is η, then

$$U_H = \eta\frac{u_{*0}}{\kappa}\ln\frac{z}{z_{00}} \quad (17)$$

So that (16) becomes

$$\frac{z_0}{H} = (1-\frac{d}{H})\exp\left[\phi - \frac{u_*}{u_{*0}}(\eta\cdot\ln\frac{H}{z_{00}})\right] \quad (18)$$

in which all terms are known or can be evaluated except for η and ϕ. Based on wind tunnel data, η was depended on the canopy density of sparse trees and the empirical relation was

$$\eta = 0.55e^{-7.0C} + 0.45 \quad (19)$$

with correlation 0.980.

Let

$$a = \eta\ln(H/z_{00}) = (0.55e^{-7.0C}+0.45)\ln(H/z_{00})$$

then

$$\frac{z_0}{H} = (1-\frac{d}{H})\exp(\phi - \frac{a}{u_*/u_{*0}}) \quad (20)$$

From measurement data and calculation by model (15) we deduced that ϕ is related to C as follow

$$\phi = \begin{cases} 0.9 & C \geqslant 0.2 \\ 4.5C & C < 0.2 \end{cases} \quad (21)$$

with correlation 0.966.

The model values and the "measurements" are shown in Fig.2. The "measurements" of Z_0/H were the results of calculation by approximation method based on wind tunnel and field data (Guan 1997). It can be seen that the model agrees well with "measurements".

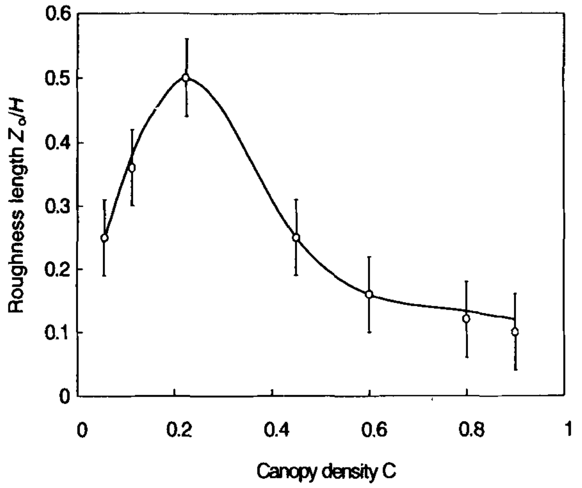

Fig. 2. Comparison of the model values (line) and the "measurements"(dots)

Conclusions and discussions

Sparse-tree land is one of the typical lands and can be considered as one typical rough surface in boundary layer meteorology. Many lands can be classified into the kind surface in the view of scale and distribution feature of the roughness elements such as agroforest, scatter planted or growing trees, savanna and so on. This paper gives the models of friction velocity u_* and roughness length z_0 of this kind surface based on physical laws and some empirical relations. The models agree well with measurements and calculated results from measurements.

The authors think that this study is preliminary and more deep analysis and measurement are expected.

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